Scientific Paper / Artículo Científico

UNIVERSIDAD POLITÉCNICA SALESIANA ECUADOR
INGENIUS
Revista de Ciencia y Tecnología
https://doi.org/10.17163/ings.n36.2026.05
pISSN: 1390-650X / eISSN: 1390-860X

VULNERABILITY AND RISKS OF ECUADOR'S ENERGY SYSTEM IN THE CONTEXT OF CLIMATE CHANGE AND ENVIRONMENTAL SUSTAINABILITY POLICIES

VULNERABILIDAD Y RIESGOS DEL SISTEMA ENERGÉTICO ECUATORIANO FRENTE AL CAMBIO CLIMÁTICO Y LAS POLÍTICAS DE SOSTENIBILIDAD AMBIENTAL

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Received: 05-08-2025, Received after review: 09-03-2026, Accepted: 21-04-2026, Published: 01-07-2026

Abstract

This study examines future CO_2 emissions scenarios for Ecuador by 2050, considering the interrelationships among energy supply, energy demand, and economic growth. Using a system dynamics modeling approach, three scenarios were developed: a Business-as-Usual (BAU) scenario, an optimistic national policy scenario (ESCN1), and a global trends scenario (ESCN2). The model was calibrated and validated using historical data from 2000 to 2015 and then applied to simulate the long-term behavior of CO_2 emissions associated with final energy consumption across six key economic sectors. The results indicate that, under the BAU and ESCN1 scenarios, both energy demand and CO_2 emissions are projected to increase significantly, driven by continued dependence on fossil fuels. In contrast, the ESCN2 scenario, aligned with international sustainability trends and policy frameworks, suggests a potential reduction in emissions by 2050 through a more diversified energy mix and improvements in energy efficiency.

Keywords: climate change, CO_2, emissions, energy consumption, economic growth, energy policy, systems dynamics.

Resumen

Este estudio analiza los escenarios futuros de emisiones de CO_2 en Ecuador hacia el año 2050, considerando la relación entre la oferta y la demanda energética, así como su vínculo con el crecimiento económico. Mediante un enfoque de modelado basado en la dinámica de sistemas, se desarrollaron tres escenarios: un escenario tendencial (BAU), un escenario optimista con políticas nacionales (ESCN1) y un escenario alineado con las tendencias globales (ESCN2). El modelo fue calibrado y validado con datos históricos del período 2000-2015 y se aplicó para simular el comportamiento a largo plazo de las emisiones de CO_2 derivadas del consumo final de energía en seis sectores económicos clave. Los resultados muestran que, bajo los escenarios BAU y ESCN1, se proyecta un aumento significativo de la demanda energética y de las emisiones de CO_2, debido a la persistente dependencia de los combustibles fósiles. En contraste, el escenario ESCN2, alineado con políticas internacionales de sostenibilidad, sugiere una posible reducción de emisiones hacia 2050 mediante una matriz energética diversificada y mejoras en eficiencia energética.

Palabras clave: cambio climático, consumo energético, crecimiento económico, emisiones CO_2, política energética, sistemas dinámicos.

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Suggested citation: F. Arroyo-Morocho, D. Bravo-Donoso, A. Remache-Coyago and T. Freire-Rosero "Vulnerability and risks of Ecuador's energy system in the context of climate change and environmental sustainability policies," *Ingenius, Revista de Ciencia y Tecnología*, N.° 36, pp. 54-69, 2026, DOI: https://doi.org/10.17163/ings.n36.2026.05.

1. Introduction

Development agendas over the past decade have been shaped by the impacts of global warming, increasing the need for mitigation strategies that account for both economic and environmental costs [1–4]. Although the global transition remains insufficient, with 82% of energy demand still dependent on fossil fuels, renewable energy capacity additions reached 507 GW in 2023 [5–8].Ecuador illustrates a paradox in this context: despite its negligible contribution to global emissions, its carbon dioxide emissions reached 35.5 $MtCO_2$ in 2021, revealing a close association between GDP growth and the intensive use of carbon-based energy [9–11] as shown in Figure 1.

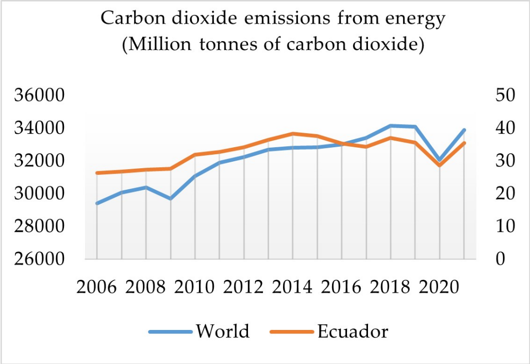


Figure 1. CO_2 emissions (2007 – 2021)

Previous studies indicate that economic growth in developing countries typically leads to increased energy demand [12–17]. Unless deliberate policy interventions are implemented, technological innovation alone cannot decouple emissions from economic growth. In Ecuador, earlier research has examined electricity sector reform and historical trends separately [18,19]. However, to date, no dynamic model has been developed that systematically integrates GDP growth, sectoral energy consumption, and long-term emissions pathways [20–24]. This article employs System Dynamics (SD) to capture time delays and feedback loops, thereby enabling the simulation of transition pathways toward 2050.

System dynamics (SD) has proven to be a valuable approach for analyzing complex socio-ecological systems and exploring sustainable future scenarios [25–27]. Modeling energy systems is particularly challenging because of the involvement of multiple decision-makers and heterogeneous patterns of consumer behaviors. The main advantage of SD lies in its ability to capture nonlinear dynamics, feedback loops, and time delays [28].

A system dynamics–based model has been developed to analyze the behavior of the socio -energy-economic-climate system, concluding that climate policy plays a key role in the design of evaluation models for the energy-based economic sector [29]. In addition, a dynamic simulation model has been developed to examine household energy consumption and CO_2 emissions under different conditions [30].

Extensive research has examined the relationship between economic growth and carbon emissions resulting from energy consumption [31–33]. The effects of different types of energy consumption on economic growth and emissions vary across groups of countries. In addition, the causal relationship between overall economic growth and energy consumption is bidirectional [34–36].

Dynamic causal relationships among energy consumption, CO_2 emissions, and economic growth have been examined using advanced multivariate modeling approaches, thereby overcoming bias associated with omitted variables and uncertainty regarding the stationarity properties of time-series variables [37,38].

Previous studies in Ecuador have examined the impact of national energy policies on the energy transition during 2007–2014 [27], [39], electricity sector reform and its vulnerability to climate change [40], and long-term trends in carbon emissions and energy consumption over the 1980–2025 period [24]. These analyses confirm that economies dependent on fossil fuels generate higher emissions than those that diversify their energy mix toward renewable sources [8], [28]. However, few studies have integrated these perspectives into dynamic scenario modeling, underscoring the need for a comprehensive approach such as that proposed in this research.

Ecuador's primary energy matrix has historically been dominated by oil, with only a limited contribution from renewable sources, as illustrated in Figure 2. Nevertheless, hydroelectric generation increased by more than 200% between 2000 and 2022, while wind and photovoltaic generation began contributing after 2007.

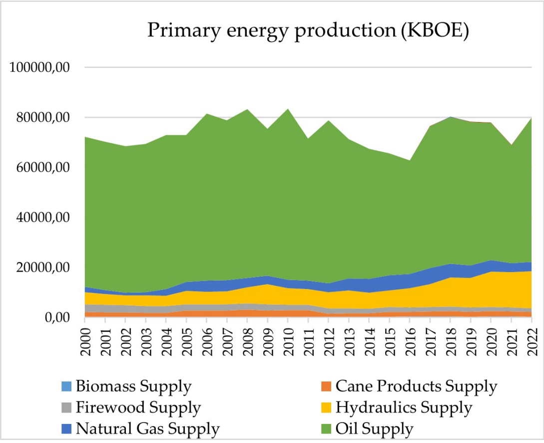


Figure 2. Evolution of primary energy production (2000 – 2022)

Secondary energy production increased by more than 46% between 2000 and 2022, as shown in Figure 3. Fuel oil and diesel have remained the dominant sources; however, since 2014, electricity generation has increased sharply and has nearly reached the level of diesel.

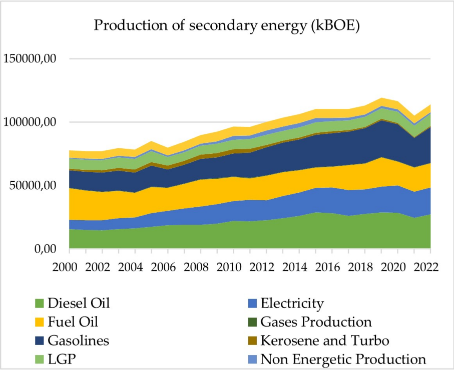


Figure 3. Evolution of secondary energy production (2000 – 2022).

Final energy consumption in Ecuador is distributed across s seven sectors. By 2015, transport accounted for nearly half of total demand, followed by industry and households. Despite slight increases in the transport and residential sectors, overall demand declined mainly due to a marked reduction in industrial energy consumption.

1.1. Research gap and contribution

Although several studies have examined the relationships among energy consumption, economic growth, and CO_2 emissions in Ecuador, most have focused on econometric analyses or historical trends. However, only a limited number of studies have explored these interactions using dynamic simulation approaches that enable the evaluation of long-term policy scenarios.

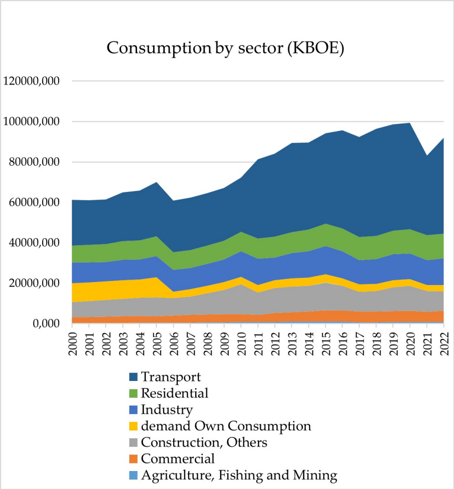


Figure 4. Evolution of secondary energy production (2000 - 2022).

In this context, the present study develops a system dynamics model that integrates economic growth, sectoral energy consumption, and CO_2 emissions to explore possible trajectories of Ecuador's energy system up to 2050. The model enables the evaluation of different policy scenarios and provides insights into the potential effects of energy transition strategies on future emissions.

2. Materials and Methods

System dynamics models can be developed through user-friendly interfaces. These model development procedures are based on a visualization process that enables modelers to conceptualize, document, simulate, and analyze dynamic systems [41]. In essence, the system dynamics approach seeks to represent problems from a dynamic perspective.

Three scenarios were developed. The first, the Business-as-Usual (BAU) scenario, represents the continuation of current system conditions without additional policy intervention. The second, ESCN1, is an optimistic national policy scenario that incorporates government policies and official projections. The third, ESCN2, is a regional or global scenario based on broader trends observed in countries across the region and worldwide.

The study develops a system dynamics model to estimate CO_2 emissions by Ecuador in 2050. It aims to examine the relationships among CO_2 emissions over time, energy consumption, and Ecuador's economic growth. The main variables determining CO_2 emissions are economic growth and energy consumption.

The case study method enables the investigation of real-life phenomena through detailed contextual analysis of a limited number of events or conditions and their interrelationships [42]. It is also defined as an empirical research approach for investigating a contemporary phenomenon within its real-life context [43].

The model's main hypothesis is that CO_2 emissions in Ecuador are not an isolated phenomenon, but rather the result of a positive feedback loop between sectoral energy demand and economic growth (GDP). It assumes that, under business-as-usual conditions, economic growth leads to higher energy demand. This demand, largely met through fossil fuels with fixed emission factors, results in a cumulative increase in emissions. In contrast, intervention through energy efficiency measures and energy transition policies operates as a balancing mechanism aimed at decoupling GDP growth from carbon intensity.

The model is structured around the interaction of three key subsystems: Economic Growth, Final Energy Demand, and CO_2 Emissions.

- **Economic Subsystem:** Determines the pace of the system through capital accumulation and production, represented by GDP.
- **Demand Subsystem:** Translates economic activity into sectoral energy requirements (e.g., transport, industry, and residential use), as determined by energy intensity and technological improvements.
- **Emissions Subsystem:** Represents the environmental impact associated with the consumption of different energy sources by applying specific emission factors.

2.1. Scenario construction

Scenario planning is a technique that, rather than seeking prediction, offers alternative ways of thinking about the future based on plausible possibilities [44,45]. This approach enables the exploration of a range of alternative futures. Scenario construction can also be regarded as a subset of strategic forecasting, defined as the development of multiple possible futures to support strategy [46,47].

This process is based on assumptions about how the future might unfold, including the directions in which certain trends may evolve, which developments might remain constant, and which might change over time. Scenarios describe pathways toward possible futures [48]. They reflect different assumptions about how current trends may develop, how critical uncertainties may play out, and what new factors may emerge.

A series of scenarios was developed to identify trends in energy intensity and CO_2 emissions associated with final energy consumption in Ecuador. The scenarios necessarily incorporate subjective elements and remain open to different interpretations. Their formulation is essential for anticipating the evolution of the main variables, informing energy policy, and projecting future energy consumption patterns and CO_2 mitigation pathways.

For research purposes, three scenarios were proposed. The first, BAU, represents the continuation of current system conditions under unchanged assumptions. ESCN1 considers the policies proposed by the national government for future projections. ESCN2 reflects global trends observed in industrialized countries.

Scenario 1 (BAU) represents the continuation of existing conditions. It projects the current trends identified at the national level, assuming that past trends will persist and that no new policies affecting energy production and consumption will be implemented.

Scenario 2 (ESCN1) considers the government plans and strategies established in Ecuador for the coming years regarding energy production and consumption. The following documents are taken into account: National Energy Agenda 2016 – 2040 [49], National Energy Balance 2013 – 2017 [50–55], National Energy Efficiency Plan 2016 – 2035 [56], Electricity Master Plan 2016 – 2025 [57], Electrification Master Plan 2013 – 2022 [58], Analysis of R & D & I opportunities in Energy Efficiency and Renewable Energies in Ecuador [59], National Climate Change Strategy of Ecuador 2012 – 2025 [60], Sustainable Energy for All: Rapid Assessment Gap Analysis Ecuador [61], and Ecuador Renewable Energy [62].

Scenario 3 (ESCN2) considers the environmental dimension of sustainable development goals, global environmental governance, multilateral environmental agreements, and global macroeconomic perspectives for addressing climate change and its impacts, as well as transition plans related to clean energy and energy efficiency. The scenario also draws on projections and trends reported by organizations such as the Intergovernmental Panel on Climate Change (IPCC), [63–65] the International Energy Agency (IEA) [2], [66–71] and BP [11], among others.

2.2. Modeling and simulation

The proposed system dynamics model was simulated using Vensim, a modeling tool for building, simulating, and analyzing dynamic systems with causal loop and stock-and-flow diagrams. This model estimates Ecuador's energy consumption, economic growth, and CO_2 emissions up to 2050, considering the country's conventional energy resources. It also examines the impact of economic growth on energy consumption and CO_2 emissions. Figure 5 presents the flow diagram of the economic-energy-CO_2 emissions system, illustrating these interactions. CO_2 emissions result from final energy demand across Ecuador's economic sectors.

The model integrates three subsystems: economic growth, final energy demand, and CO_2 emissions. Economic activity drives the evolution of energy consumption across different sectors of the economy, while emissions result from the use of energy carriers associated with specific emission factors. At the macro level, economic growth is represented by the evolution of gross domestic product (GDP), which follows an annual growth rate defined for each scenario:

$$GDP_t = GDP_{t-1}(1 + g_t) \qquad (1)$$

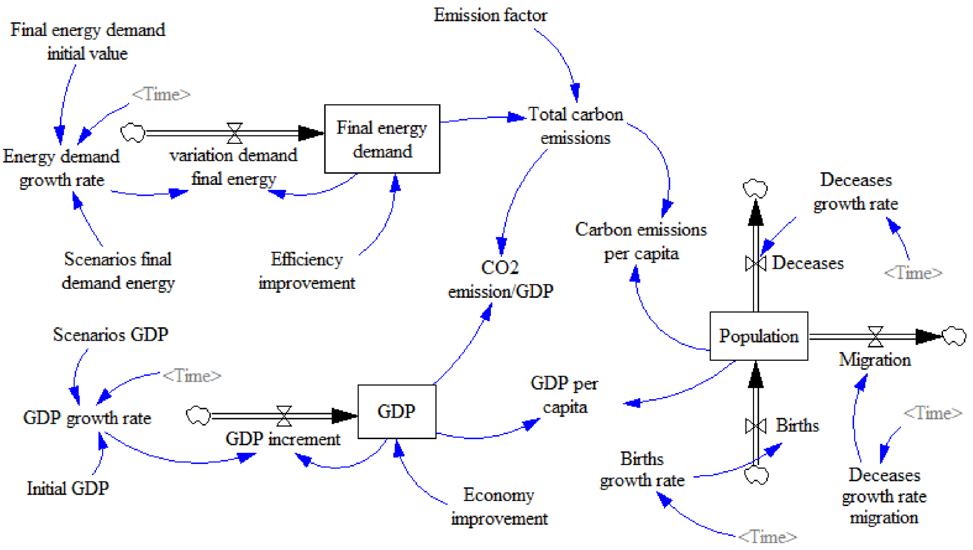


Figure 5. Economic – energy - carbon emissions system flow diagram in Ecuador.

where GDP_t represents the gross domestic product in year t, and g_t is the annual economic growth rate.

Final energy demand is estimated as the aggregate of sectoral energy consumption across the main economic sectors considered in the model:

$$FED_t = \sum_{s=1}^{n} ED_{s,t} \tag{2}$$

where FED_t denotes the total final energy demand, and $ED_{s,t}$ represents the energy demand of sector s in year t.

Sectoral energy demand is assumed to depend on the level of economic activity and the corresponding energy intensity:

$$ED_{s,t} = GDP_t \cdot EI_{s,t} \tag{3}$$

where $EI_{s,t}$ represents the energy intensity of sector s, expressed as the amount of energy required per unit of economic output.

To represent improvements in energy efficiency and technological change, sectoral energy intensity evolves over time according to:

$$EI_{s,t} = EI_{s,t-1}(1 - \eta_s) \tag{4}$$

where η_s represents the annual rate of improvement in energy efficiency for sector s.

CO_2 emissions are estimated from energy consumption by applying the emission factors associated with each energy carrier:

$$CO2_t = \sum_{i=1}^{m} EC_{i,t} \cdot EF_i \tag{5}$$

where $EC_{i,t}$ represents the consumption of energy carrier i in year t, and EF_I is the corresponding emission factor.

Within the system dynamics framework implemented in Vensim, these relationships interact through feedback mechanisms linking economic activity, energy demand, and emissions. The three scenarios analyzed in this study, BAU, ESCN1, and ESCN2, modify key parameters, such as economic growth rates, improvements in energy efficiency, and the composition of the energy mix, to simulate alternative future trajectories of Ecuador's energy system up to 2050.

2.3. Model validation

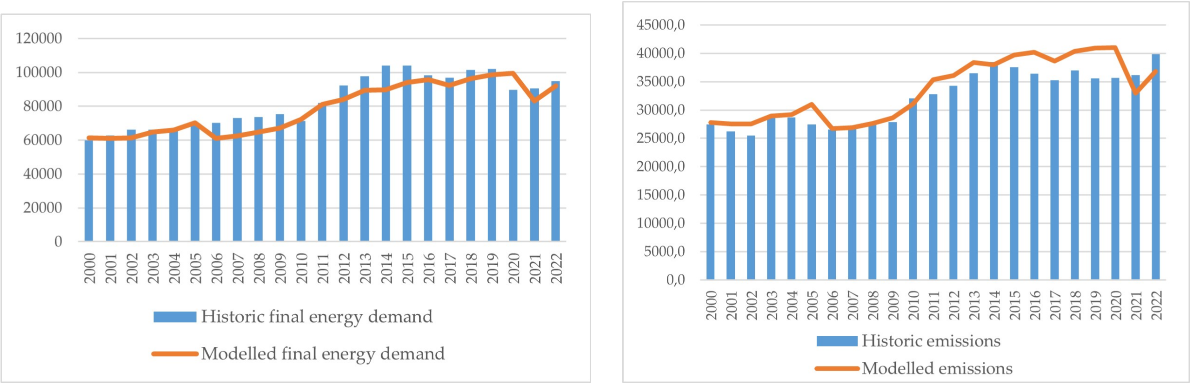
Validation is the overall process of comparing the model's behavior with that of the real system [72]. No model exactly matches the system under study, because all models are, to some extent, simplifications of the systems they represent [73]. The quality of a study conducted using a simulation model depends largely on its validation [74]; accordingly, verification and validation are among the key stages in simulation development [75]. Validation remains an essential yet controversial and unresolved aspect of the modeling methodology [76]. Social scientists acknowledge the impossibility of absolute validation, the provisional nature of all models, and the need for a more eclectic and diverse set of tests [77].

System dynamics modelers are generally more concerned with dynamic trends than with the specific values of system variables in particular years. In practice, the usefulness of a model is a central concern. Confidence is often regarded as the most appropriate criterion for assessing model behavior, since there is no absolute proof that a model can fully represent reality.

System dynamics models are considered valid when they can be used with confidence [78].

After calibration using the original system data set, the model undergoes a final validation based on a second data set. The validation of a system dynamics model comprises two broad components: structural validation and behavioral validation. Structural validation involves establishing that the relationships used in the model adequately represent the real-world relationships relevant to the purpose of the study. Behavioral validation consists of demonstrating that the model's behavior is sufficiently close to the observed behavior [79].

The model was initially validated by comparison with official data for the 2000–2015 period. Figure 6(a) presents the comparison between simulated and historical energy demand across the consumption sectors responsible for CO_2 emissions in Ecuador. Figure 6(b) presents the comparison between simulated and historical CO_2 emissions. These results indicate that the model is capable of reproducing the structure of the real system and generating meaningful projections. The model also provides a useful basis for designing new policies to improve the system's future behavior.



(a) (b)

Figure 6. (a) Historical and simulated final energy demand; (b) historical and simulated CO_2 emissions in Ecuador, 2000 – 2022.

Statistical validation was performed using two methods. The first was the AME method, which measures the average deviation between empirical data and simulated data. It can be expressed mathematically as follows:

$$AME(\%) = \frac{D_s - D_e}{De} x100 \tag{6}$$

where AME represents the Average Mean Error, D_s denotes the simulated data, and D_e is the empirical data.

The second validation method involved calculating the mean absolute percentage error (MAPE), defined as follows:

$$MAPE(\%) = \frac{1}{n} \sum \left| \frac{(A_t - F_t)}{A_t} \right| x100 \tag{7}$$

where MAPE denotes the mean absolute percentage error, A_t, F_t and n represent the real data, the calculated values, and the number of data, respectively.

Table 1 presents the values obtained using the AME and MAPE methods. These results indicate the robustness of the model. It should be noted that, in this study, CO_2 emissions are assumed to result from the combustion of fossil fuels consumed by Ecuador's six economic sectors.

In addition to the graphical comparison of simulated and historical data, model validation included the calculation of the Absolute Percentage Error (APE) and the Mean Absolute Percentage Error (MAPE). These indicators provide quantitative measures of the deviation between simulated and observed values. In energy system modeling, MAPE values of approximately 10% to 15% are commonly considered acceptable for medium- and long-term projections, particularly when the model's objective is to reproduce system trends rather than exact annual observations. In this case, the error values obtained fall within this range, indicating that the model adequately captures the historical evolution of energy demand and emissions in Ecuador.

System dynamics models are primarily designed to reproduce the structural behavior of complex systems rather than to generate probabilistic forecasts. For this reason, validation is typically based on structural consistency tests and the reproduction of historical trends, rather than on statistical confidence intervals.

Table 1. Model validation results

	Energy demand				**CO_2 emissions**			
Year	**Real Data (KBOE)**	**Simulated (KBOE)**	**AME (%)**	**MAPE (%)**	**Real Data (Megatonnes CO_2)**	**Simulated (Megatonnes CO_2)**	**AME (%)**	**MAPE (%)**
2000	59911	61209	2.12	0.022	27477.0	27750.6	0.99	0.01
2001	62816	61126	-2.76	0.027	26299.0	27570.9	4.87	0.05
2002	66311	61357	-8.07	0.075	25480.0	27540.2	7.48	0.08
2003	66119	64838	-1.98	0.019	28601.0	28935.9	1.14	0.01
2004	66713	65832	-1.34	0.013	28709.0	29182.3	1.62	0.02
2005	69808	70109	0.43	0.004	27491.0	31021.8	11.38	0.13
2006	70265	60923	-15.33	0.133	26540.0	26690.2	0.56	0.01
2007	72985	62384	-16.99	0.145	27010.0	26918.3	-0.34	0.00
2008	73817	64649	-14.18	0.124	27500.0	27584.1	0.30	0.00
2009	75463	67101	-12.46	0.111	27900.0	28571.8	2.35	0.02
2010	71303	72382	1.49	0.015	32100.0	31038.0	-3.42	0.03
2011	81943	81242	-0.86	0.009	32800.0	35325.4	7.15	0.08
2012	92303	84051	-9.82	0.089	34300.0	36109.7	5.01	0.05
2013	97882	89473	-9.40	0.086	36500.0	38351.0	4.83	0.05
2014	104100	89610	-16.17	0.139	38500.0	37965.0	-1.41	0.01
2015	104084	94155	-10.55	0.095	37600.0	39712.4	5.32	0.06
2016	98353	95656	-2.82	0.027	36400.0	40168.0	9.38	0.10
2017	97023	92386	-5.02	0.048	35300.0	38596.7	8.54	0.09
2018	101537	96435	-5.29	0.050	37000.0	40336.9	8.27	0.09
2019	102133	98697	-3.48	0.034	35600.0	40899.1	12.96	0.15
2020	89705	99444	9.79	0.109	35683.0	40991.7	12.95	0.15
2021	90719	83134	-9.12	0.084	36180.0	32950.5	-9.80	0.09
2022	94957	92046	-3.16	0.031	39852.0	36792.1	-8.32	0.08
				9.31				8.56

2.4. Sensitivity analysis

System dynamics has long featured a sophisticated, flexible approach to testing. The sensitivity of results must be evaluated with respect to uncertainty in assumptions, whether parameters are estimated critically or by statistical means [80]. In the early 1990s, William Nordhaus developed the DICE (Dynamic Integrated Climate Economy) model, which was one of the first and most influential of the so-called "Integrated Climate Economy Models" [81, 82].

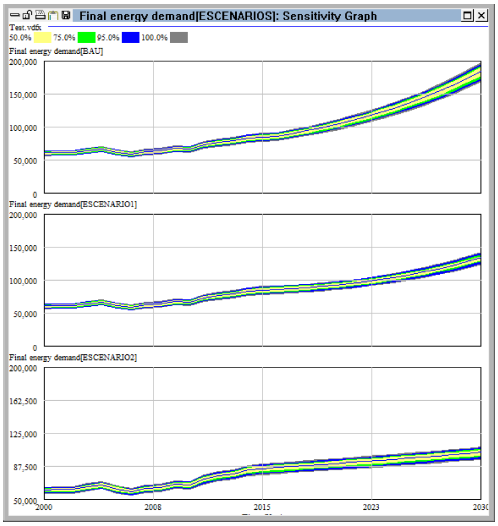


Figure 7. Energy demand scenarios for the sensitivity analysis, generated with Vensim.

The sensitivity analysis is performed to identify the system's behavior as key parameters vary. Since improvements in energy efficiency and economic growth significantly affect energy consumption and CO_2 emissions, three scenarios are designed to test the model's sensitivity figure 7.

3. Results and Discussion

3.1. Final energy demand

The model projects divergent behaviors depending on the stringency of the policies implemented [4], [83], as shown in Figure 8:

- **Business-as-usual scenario:** Demand is projected to increase by 1.21 times relative to the base year, with oil and natural gas, used primarily for transport and energy production, remaining the dominant energy sources. The system's vulnerability is reflected in its reliance on imported hydrocarbons to compensate for infrastructure deficit.

- **In contrast to the business-as-usual scenario, National Policies Scenario 1 (NSP1)**: anticipates a 2.23-fold increase in demand despite official planning. Demand growth in the transport and industrial sectors exceeds the benefits of current efficiency policies, suggesting that existing targets are insufficient to curb energy intensity.

- **Global Trend Scenario 2 (NSP2):** This is the only scenario that achieves a net 10% reduction in demand by 2050. The success of this trajectory lies in the aggressive substitution of fossil fuels with electricity and in efficiency improvements that offset the effects of economic growth.

The gradual decline in the use of fossil fuels, particularly gasoline and diesel, underscores the effectiveness of policies aimed at reducing carbon emissions and promoting clean energy technologies. The steady demand for natural gas and electricity suggests a transition toward these lower-carbon energy sources without a substantial increase in total energy consumption.

In this scenario, government energy policies emphasize a pragmatic strategy that advances both energy efficiency and a diversified energy supply mix. This approach likely includes stricter efficiency standards, support for renewable energy sources, and progress in energy storage and distribution technologies.

In the transport sector, the BAU scenario projects that, by 2050, energy consumption, driven primarily by diesel oil and gasoline, will account for 34% of the national energy consumption matrix relative to the base year, as shown in Figure 8. This sector remains highly inefficient because of its strong dependence on fossil fuels. By comparison, the ESCN1 scenario projects final energy demand at 69% of the sector's base-year level, reflecting significant growth in transport needs and the limited mitigating effect of energy efficiency policies. In contrast, the ESCN2 scenario projects demand at 27% of the base-year level, likely due to more aggressive policies and the adoption of alternative energy sources, resulting in a substantial reduction in fossil fuel dependency and more effective containment of energy demand growth. These results clearly distinguish ESCN1 as reflecting more moderate interventions, whereas ESCN2 represents stronger shifts in policy and technology.

These scenarios illustrate how policy interventions can differ in their impact. ESCN1 suggests that moderate measures may be insufficient to offset rising energy demand. In contrast, ESCN2 indicates that comprehensive strategies could enhance energy efficiency and reduce reliance on fossil fuels in the transport sector by 2050.

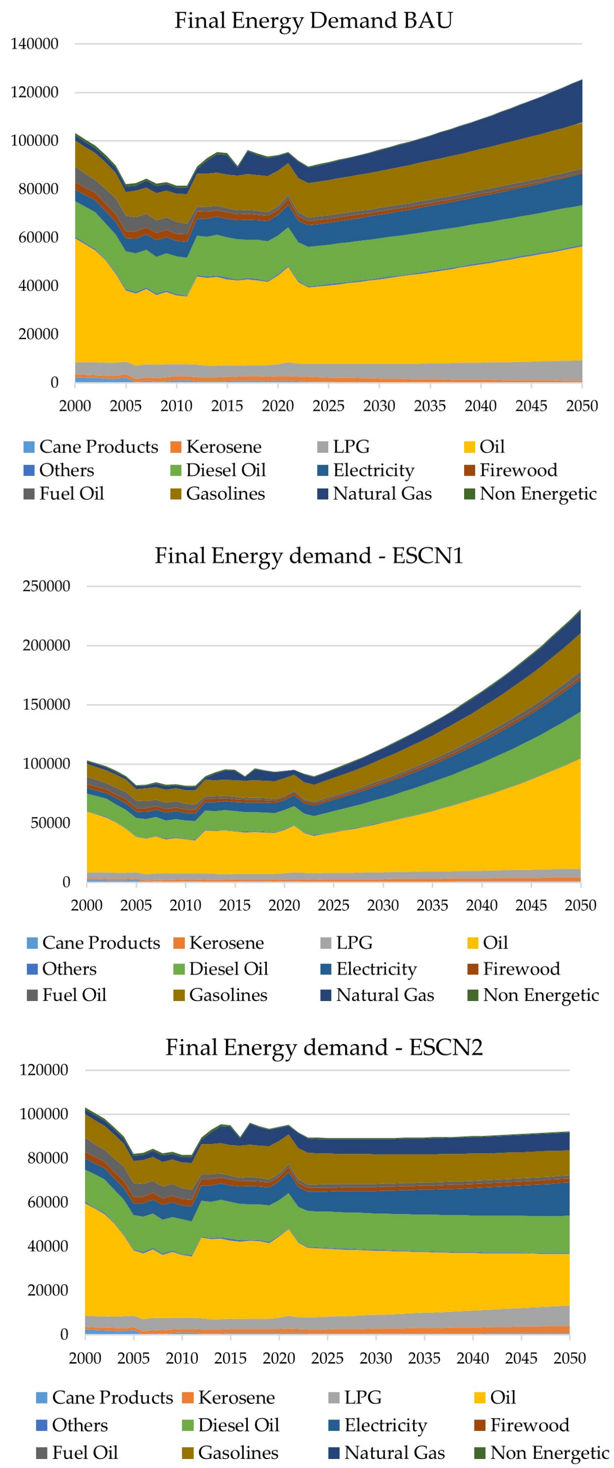


Figure 8. Final energy demand scenarios.

3.2. CO_2 emissions

According to the sectoral analysis, the transport sector is the main source of emissions, accounting for 34% of the total under the business-as-usual scenario, as shown in Figure 9. The emissions projections indicate the following:

- Under ESCN1, emissions increase by 145% as the expected growth in economic activity exceeds the decarbonization rate of the current energy matrix.
- Under ESCN2, emissions decrease by 5%, driven by the adoption of clean generation technologies and compliance with international sustainability standards.

These results indicate that the expansion of the Ecuadorian economy should not be viewed as an impediment, but rather as a driving force for investment in new mitigation technologies and in research and development.

Replacing fossil fuels by harnessing the country's remaining hydroelectric potential appears to be the most viable pathway for reducing emissions from the current 37.10 $MtCO_2$ to levels below 20 $MtCO_2$.

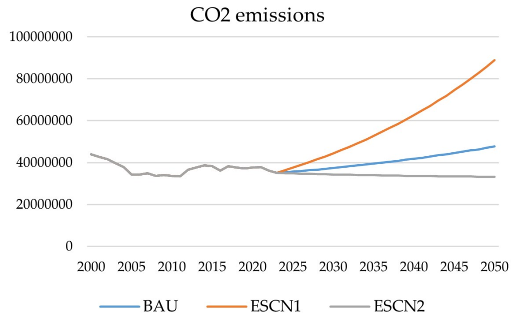


Figure 9. CO_2 emissions ($KTCO_2$)

The results of this study are consistent with previous research indicating a strong relationship among economic growth, energy consumption, and CO_2 emissions. Several studies have shown that, in developing economies, economic expansion is usually accompanied by increased energy demand [84,85], particularly when fossil fuels remain dominant in the energy mix [86]. In the Ecuadorian context, this relationship is especially evident in the transport and industrial sectors, which account for a significant share of final energy consumption.

Similar trends have been reported in studies analyzing energy transition scenarios in Latin America [87–89], where dependence on fossil fuels continues to drive emissions growth despite increasing investments in renewable energy. These findings reinforce the importance of improving energy efficiency and promoting structural changes in the energy system to reduce long-term emissions.

From a policy perspective, the scenario analysis highlights the importance of implementing long-term energy transition strategies. The results suggest that maintaining current trends under the BAU scenario could lead to a sustained increase in both energy demand and CO_2 emissions. In contrast, scenarios incorporating stronger policy interventions and technological improvements indicate a potential stabilization or reduction of emissions over time [90].

These results support the need for policies aimed at increasing the share of renewable energy, improving energy efficiency, and reducing dependence on fossil fuels in key sectors of the Ecuadorian economy.

These results support the need for policies aimed at increasing the share of renewable energy, improving energy efficiency, and reducing dependence on fossil fuels in key sectors of the Ecuadorian economy.

Despite the usefulness of the proposed model for exploring long-term trends, several limitations should be acknowledged. First, the model relies on historical data and assumptions regarding economic growth, energy intensity, and policy implementation, all of which introduce uncertainty in long-term projections. Second, the model represents the energy system at an aggregated level and does not explicitly account for technological diffusion processes or behavioral changes in energy consumption. Finally, the scenarios analyzed are based on simplified assumptions about future policy and economic conditions, which may unfold differently in practice.

3.3. Discussion and Limitations

Although the systems dynamics analysis employed in this study provides a useful framework for examining the long-term interactions among energy demand, economic growth, and CO_2 emissions, several limitations associated with the scenario assumptions should be considered.

The scenarios are based on simplified assumptions regarding future rates of economic growth, changes in energy intensity, and shifts in the energy mix. These variables are influenced by various external factors, such as international energy prices, regulatory changes, technological innovation, and geopolitical conditions.

Structural changes in the economy, such as the digitization of industrial processes, the widespread adoption of low-carbon technologies, and rapid electrification, may alter these relationships over time. In particular, disruptive technological change may reduce energy intensity more rapidly than assumed in the present simulations. Policy-oriented scenarios assume that international agreements and national sustainability strategies will be implemented within established time frames. In practice, however, the effectiveness of climate and energy policies depends on institutional capacity, social acceptance, and the availability of investment, which may result in the partial or delayed implementation of measures.

The model represents Ecuador's energy system at an aggregate level and therefore does not explicitly capture micro-level dynamics, such as changes in energy use, technological diffusion processes, or regional inequalities in energy access and infrastructure development. These factors may influence the actual evolution of energy demand and emissions.

Finally, uncertainties associated with climate variability were not explicitly modeled in the energy supply subsystem. Extreme weather events, such as prolonged droughts, may alter electricity availability and indirectly affect fossil fuel use and emissions due to the significant role of hydropower in Ecuador's electricity generation.

Despite these limitations, the model provides a useful analytical tool for investigating long-term trends and examining the potential consequences of different policy pathways. Therefore, the results should not be interpreted as definitive predictions of the future development of Ecuador's energy system, but rather as indicators that support strategic planning.

4. Conclusions

Economic projections alone do not offer a favorable pathway for reducing emissions in Ecuador; therefore, targeted public policies are required to improve the quality of life while advancing environmental sustainability. At the same time, the scenario analysis suggests that, as renewable energy use increases alongside continued economic growth, the relationship between these variables becomes less tightly coupled over time than it has been historically.

Investment in scientific research focused on emerging technologies and mitigation strategies must become a state priority to ensure that economic growth generates positive environmental outcomes. This effort should include strengthening local capacities in smart grid management and demand digitalization, thereby enabling more efficient load management and reducing pressure on existing infrastructure.

Since the transport sector is the largest source of emissions and accounts for 34% of the consumption matrix under the projected trend, it is necessary to move beyond a passive policy of technological substitution toward one that actively promotes the electrification of public and heavy freight transport. The findings indicate that energy efficiency alone will not be sufficient to accommodate the sector's projected growth. Therefore, tax incentives should be implemented to directly support freight infrastructure, while fossil fuel subsidies should be gradually phased out and the corresponding resources reallocated to technological innovation funds.

The results also show that energy intensity in Ecuador remains high. Strengthening the National Energy Efficiency Plan through binding regulations for industry is therefore essential. In this regard, mandatory energy audits and the adoption of international standards are required. The ultimate objective should be genuine decoupling, allowing GDP to grow while energy demand stabilizes or declines, as observed in the ESCN2 scenario trajectories.

The vulnerability of the system to climate-related events, such as droughts that adversely affect hydropower generation, also highlights the need for rapid diversification toward non-conventional renewable energy sources, particularly wind and solar photovoltaic energy. The model indicates that increasing the combined share of hydropower and renewable energy to between 50% and 70% could significantly reduce emissions to a range of 15.03 to 27.36 MtCO2. To support this transition, specific auctions for microgrids and energy storage projects should be introduced to ensure supply stability without relying on backup thermal power plants fueled by diesel or fuel oil.

Contributor Roles

- **Flavio Arroyo-Morocho:** Conceptualization, data processing, research.
- **Dely Bravo-Donoso:** Conceptualization, data processing, research.
- **Abel Remache-Coyago:** Conceptualization, formal analysis, data curation.
- **Tatiana Freire-Rosero:** Visualization, writing – review and editing.

References

[1] El Mundo. (2016, Jan.) Alerta mundial por la contaminación en las ciudades de todo el planeta. ElMundo.es. Accessed: May 19, 2026. [Online]. Available: https://upsalesiana.ec/ing36ar5r1

[2] International Energy Agency (IEA), "CO_2 emissions in 2023," International Energy Agency, Paris, France, Tech. Rep., 2024, accessed: May 19, 2026. [Online]. Available: https://upsalesiana.ec/ing36ar5r2

[3] P. K. Wesseh and B. Lin, "Energy consumption, fuel substitution, technical change, and economic growth: Implications for CO_2 mitigation in Egypt," *Energy Policy*, vol. 117, pp. 340–347, 2018. [Online]. Available: https://doi.org/10.1016/j.enpol.2018.03.022

[4] M. Mirzaei and M. Bekri, "Energy consumption and CO_2 emissions in Iran, 2025," *Environmental Research*, vol. 154, pp. 345–351, Apr. 2017. [Online]. Available: https://doi.org/10.1016/j.envres.2017.01.023

[5] J. Emmerling, P. Andreoni, and M. Tavoni, “Global inequality consequences of climate policies when accounting for avoided climate impacts,” *Cell Reports Sustainability*, vol. 1, no. 1, p. 100008, Jan. 2024. [Online]. Available: https://doi.org/10.1016/j.crsus.2023.100008

[6] S. Baik, J. F. Hines, and J. Sim, “Racial disparities in the energy burden beyond socioeconomic inequality,” *Energy Economics*, vol. 127, p. 107098, Nov. 2023. [Online]. Available: https://doi.org/10.1016/j.eneco.2023.107098

[7] M. K. Ardakani and S. M. Seyedaliakbar, “Impact of energy consumption and economic growth on CO_2 emission using multivariate regression,” *Energy Strategy Reviews*, vol. 26, p. 100428, Nov. 2019. [Online]. Available: https://doi.org/10.1016/j.esr.2019.100428

[8] F. Arroyo and L. J. Miguel, “Analysis of energy demand scenarios in Ecuador: National government policy perspectives and global trend to reduce CO_2 emissions,” *International Journal of Energy Economics and Policy*, vol. 9, no. 2, Mar. 2019. [Online]. Available: https://doi.org/10.32479/ijeep.7132

[9] International Energy Agency (IEA), “Renewables 2023: Analysis and forecast to 2028,” International Energy Agency, Paris, France, Tech. Rep., 2024, accessed: May 19, 2026. [Online]. Available: https://upsalesiana.ec/ing36ar5r9

[10] Energy Institute, *Statistical Review of World Energy 2024*, 73rd ed. London, United Kingdom: Energy Institute, 2024, accessed: May 19, 2026. [Online]. Available: https://upsalesiana.ec/ing36ar5r10

[11] BP, *bp Statistical Review of World Energy 2022*, 71st ed. Whitehouse Associates, London, Jun. 2022, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r73

[12] A. O. Acheampong and E. E. O. Opoku, “Environmental degradation and economic growth: Investigating linkages and potential pathways,” *Energy Economics*, vol. 123, p. 106734, 2023. [Online]. Available: https://doi.org/10.1016/j.eneco.2023.106734

[13] F. R. Arroyo M. and L. J. Miguel, “The trends of the energy intensity and CO_2 emissions related to final energy consumption in Ecuador: Scenarios of national and worldwide strategies,” *Sustainability*, vol. 12, no. 1, p. 20, Dec. 2019. [Online]. Available: https://doi.org/10.3390/su12010020

[14] Q. Li, W. Zhang, H. Li, and P. He, “CO_2 emission trends of China’s primary aluminum industry: A scenario analysis using system dynamics model,” *Energy Policy*, vol. 105, pp. 225–235, 2017. [Online]. Available: https://doi.org/10.1016/j.enpol.2017.02.046

[15] B. Muhammad, “Energy consumption, CO_2 emissions and economic growth in developed, emerging and Middle East and North Africa countries,” *Energy*, vol. 179, pp. 232–245, 2019. [Online]. Available: https://doi.org/10.1016/j.energy.2019.03.126

[16] W. Xia, N. Apergis, M. F. Bashir, S. Ghosh, B. Doğan, and U. Shahzad, “Investigating the role of globalization, and energy consumption for environmental externalities: Empirical evidence from developed and developing economies,” *Renewable Energy*, vol. 183, pp. 219–228, Jan. 2022. [Online]. Available: https://doi.org/10.1016/j.renene.2021.10.084

[17] M. A. González-Álvarez and A. Montañés, “CO_2 emissions, energy consumption, and economic growth: Determining the stability of the 3E relationship,” *Economic Modelling*, vol. 121, p. 106195, Apr. 2023. [Online]. Available: https://doi.org/10.1016/j.econmod.2023.106195

[18] F. Ozturk, “Energy consumption–GDP causality in MENA countries,” *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 12, no. 3, pp. 231–236, Mar. 2017. [Online]. Available: https://doi.org/10.1080/15567249.2015.1072597

[19] E. Cifci and M. E. Oliver, “Reassessing the links between GHG emissions, economic growth, and the UNFCCC: A difference-in-differences approach,” *Sustainability*, vol. 10, no. 2, p. 334, Jan. 2018. [Online]. Available: https://doi.org/10.3390/su10020334

[20] K. Saidi and S. Hammami, “The impact of CO_2 emissions and economic growth on energy consumption in 58 countries,” *Energy Reports*, vol. 1, pp. 62–70, Nov. 2015. [Online]. Available: https://doi.org/10.1016/j.egyr.2015.01.003

[21] M. S. Shabbir, M. Shahbaz, and M. Zeshan, “Renewable and nonrenewable energy consumption, real GDP and CO_2 emissions nexus: A structural var approach in Pakistan,” *Bulletin of Energy Economics (BEE)*, vol. 2, no. 3, pp. 91–105, 2014, accessed: May 19, 2026. [Online]. Available: https://upsalesiana.ec/ing36ar5r21

[22] M. Sterpu, G. Soava, and A. Mehedintu, “Impact of economic growth and energy consumption on greenhouse gas emissions: Testing environmental

curves hypotheses on EU countries," *Sustainability*, vol. 10, no. 9, p. 3327, 2018. [Online]. Available: http://doi.org/10.3390/su10093327

[23] Comisión Económica para América Latina y el Caribe (CEPAL), "La economía del cambio climático en el Ecuador, 2012," CEPAL, Santiago, Chile, Tech. Rep. LC/W.560, 2013, accessed: May 19, 2026. [Online]. Available: https://upsalesiana.ec/ing36ar5r23

[24] A. R. López, "Carbon emissions, energy consumption and sustainable development in Ecuador (1980–2025): System dynamics modelling, decomposition analysis and the environmental kuznets curve," Doctoral thesis, Universidad de Huelva, Huelva, Spain, 2014, accessed: May 19, 2026. [Online]. Available: https://upsalesiana.ec/ing36ar5r24

[25] R. A. Begum, K. Sohag, S. M. S. Abdullah, and M. Jaafar, "CO_2 emissions, energy consumption, economic and population growth in Malaysia," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 594–601, Jan. 2015. [Online]. Available: http://doi.org/10.1016/j.rser.2014.07.205

[26] L. J. Esso and Y. Keho, "Energy consumption, economic growth and carbon emissions: Cointegration and causality evidence from selected African countries," *Energy*, vol. 114, pp. 492–497, Nov. 2016. [Online]. Available: http://doi.org/10.1016/j.energy.2016.08.010

[27] J. C. Cárdenas Herrera, "Estudio de la reducción de emisiones de carbono en el Ecuador," Master's thesis, Escuela Politécnica Nacional, Quito, Ecuador, 2014, Repositorio Digital EPN. [Online]. Available: https://upsalesiana.ec/ing36ar5r27

[28] B. Lin, O. E. Omoju, and J. U. Okonkwo, "Impact of industrialisation on CO_2 emissions in Nigeria," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1228–1239, Dec. 2015. [Online]. Available: http://doi.org/10.1016/j.rser.2015.07.164

[29] G. Mavromatidis, K. Orehounig, P. Richner, and J. Carmeliet, "A strategy for reducing CO_2 emissions from buildings with the Kaya identity – a Swiss energy system analysis and a case study," *Energy Policy*, vol. 88, pp. 343–354, Jan. 2016. [Online]. Available: http://doi.org/10.1016/j.enpol.2015.10.037

[30] X. Chen, G. Wang, X. Guo, and J. Fu, "An analysis based on SD model for energy-related CO_2 mitigation in the Chinese household sector," *Energies*, vol. 9, no. 12, p. 1062, Dec. 2016. [Online]. Available: http://doi.org/10.3390/en9121062

[31] A. Mardani, D. Streimikiene, F. Cavallaro, N. Loganathan, and M. Khoshnoudi, "Carbon dioxide (CO_2) emissions and economic growth: A systematic review of two decades of research from 1995 to 2017," *Science of The Total Environment*, vol. 649, pp. 31–49, Feb. 2019. [Online]. Available: http://doi.org/10.1016/j.scitotenv.2018.08.229

[32] J. Zhou, B. Jin, S. Du, and P. Zhang, "Scenario analysis of carbon emissions of Beijing-Tianjin-Hebei," *Energies*, vol. 11, no. 6, p. 1489, 2018. [Online]. Available: http://doi.org/10.3390/en11061489

[33] R. Arango-Miranda, R. Hausler, R. Romero-López, M. Glaus, and S. P. Ibarra-Zavaleta, "Carbon dioxide emissions, energy consumption and economic growth: A comparative empirical study of selected developed and developing countries. "The role of exergy"," *Energies*, vol. 11, no. 10, p. 2668, Oct. 2018. [Online]. Available: http://doi.org/10.3390/en11102668

[34] N. Antonakakis, I. Chatziantoniou, and G. Filis, "Energy consumption, CO_2 emissions, and economic growth: An ethical dilemma," *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 808–824, Feb. 2017. [Online]. Available: http://doi.org/10.1016/j.rser.2016.09.105

[35] F. M. Mirza and A. Kanwal, "Energy consumption, carbon emissions and economic growth in Pakistan: Dynamic causality analysis," *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 1233–1240, May 2017. [Online]. Available: http://doi.org/10.1016/j.rser.2016.10.081

[36] A. Giri and G. Mohapatra, "Energy consumption, economic growth and CO_2 emissions: Empirical evidences from India," *The Empirical Econometrics and Quantitative Economics*, vol. 4, pp. 17–32, 01 2015. [Online]. Available: https://upsalesiana.ec/ing36ar5r36

[37] P. Stamatiou and N. Dritsakis, *Dynamic Modeling of Causal Relationship Between Energy Consumption, CO_2 Emissions, and Economic Growth in Italy.* Springer International Publishing, 2017, pp. 99–109. [Online]. Available: https://doi.org/10.1007/978-3-319-48454-9_8

[38] S. H. Kang, F. Islam, and A. Kumar Tiwari, "The dynamic relationships among CO_2 emissions, renewable and non-renewable energy sources, and economic growth in India: Evidence from time-varying bayesian VAR model," *Structural Change and Economic Dynamics*, vol. 50, pp. 90–101, 2019. [Online]. Available: https://doi.org/10.1016/j.strueco.2019.05.006

[39] P. R. Tayupanta Caiza, “Análisis del impacto de las políticas energéticas relacionadas con el cambio de la matriz energética del Ecuador en el período 2007–2014 y sus perspectivas al 2020,” Tesis de Maestría, Escuela Politécnica Nacional, Quito, Ecuador, 2017, consultado: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r39

[40] M. Peláez-Samaniego, M. García-Pérez, L. Cortez, J. Oscullo, and G. Olmedo, “Energy sector in Ecuador: Current status,” *Energy Policy*, vol. 35, no. 8, pp. 4177–4189, Aug. 2007. [Online]. Available: https://doi.org/10.1016/j.enpol.2007.02.025

[41] B. Dyson and N.-B. Chang, “Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling,” *Waste Management*, vol. 25, no. 7, pp. 669–679, Jan. 2005. [Online]. Available: https://doi.org/10.1016/j.wasman.2004.10.005

[42] H. V. Coombs, “Case study research defined [White paper],” *Jurnal Kemanusiaan*, 2022. [Online]. Available: https://doi.org/10.5281/zenodo.7604301

[43] R. K. Yin, *Case Study Research and Applications: Design and Methods*, 6th ed. Thousand Oaks, CA, USA: SAGE Publications, 2018, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r43

[44] J. Derbyshire and G. Wright, “Augmenting the intuitive logics scenario planning method for a more comprehensive analysis of causation,” *International Journal of Forecasting*, vol. 33, no. 1, pp. 254–266, Jan. 2017. [Online]. Available: https://doi.org/10.1016/j.ijforecast.2016.01.004

[45] D. Sarpong and J. A. Amoah, “Scenario planning: ‘ways of knowing’, methodologies and shifting conceptual landscape,” *International Journal of Foresight and Innovation Policy*, vol. 10, no. 2/3/4, p. 75, 2015. [Online]. Available: https://doi.org/10.1504/ijfip.2015.074397

[46] H. J. Duus, “Strategic scenario construction made easy,” *International Journal of Foresight and Innovation Policy*, vol. 11, no. 1/2/3, p. 167, 2016. [Online]. Available: https://doi.org/10.1504/IJFIP.2016.078349

[47] M. Amer, T. U. Daim, and A. Jetter, “A review of scenario planning,” *Futures*, vol. 46, pp. 23–40, Feb. 2013. [Online]. Available: http://doi.org/10.1016/j.futures.2012.10.003

[48] UN Environment, *Global Environment Outlook – GEO-6: Healthy Planet, Healthy People*. Cambridge University Press, May 2019. [Online]. Available: http://doi.org/10.1017/9781108627146

[49] MCSE, “Agenda energética nacional 2016–2040,” Ministerio Coordinador de Sectores Estratégicos, Quito, Ecuador, Tech. Rep., 2016, consultado: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r49

[50] ——, “Balance energético nacional 2013,” Ministerio Coordinador de Sectores Estratégicos, Quito, Ecuador, Tech. Rep., 2013, consultado: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r50

[51] ——, “Balance energético nacional 2014,” Ministerio Coordinador de Sectores Estratégicos, Quito, Ecuador, Tech. Rep., 2014, consultado: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r51

[52] Coordinating Ministry of Strategic Sectors, “National energy balance 2015,” Coordinating Ministry of Strategic Sectors, Quito, Ecuador, Tech. Rep., 2015, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r52

[53] MCSE, “Balance energético nacional 2016,” Ministerio Coordinador de Sectores Estratégicos, Quito, Ecuador, Tech. Rep., 2016, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r53

[54] MICSE, “National energy balance 2017,” Coordinating Ministry of Strategic Sectors (MICSE), Quito, Ecuador, Tech. Rep., 2017, referenced in peer-reviewed studies on Ecuadorian energy planning. [Online]. Available: https://upsalesiana.ec/ing36ar5r54

[55] Ministry of Energy and Non-Renewable Natural Resources, “National energy balance 2017,” Ministry of Energy and Non-Renewable Natural Resources, Quito, Ecuador, Tech. Rep., 2018, referenced in peer-reviewed energy studies on Ecuador. [Online]. Available: https://upsalesiana.ec/ing36ar5r55

[56] Minister of Electricity and Renewable Energy, “National energy efficiency plan 2016–2035,” Minister of Electricity and Renewable Energy, Quito, Ecuador, Tech. Rep., 2017, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r56

[57] MEER, “Plan maestro de electricidad 2016–2025,” Ministerio de Electricidad y Energía Renovable, Quito, Ecuador, Tech. Rep., 2017, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r57

[58] CONELEC, "Plan maestro de electrificación 2013–2022," National Electricity Council, Quito, Ecuador, Tech. Rep., 2013, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r58

[59] INER, "Analysis of r&d&i opportunities in energy efficiency and renewable energies in ecuador," National Institute of Energy Efficiency and Renewable Energies, Quito, Ecuador, Tech. Rep., 2016, referenced in national energy planning studies of Ecuador. [Online]. Available: https://upsalesiana.ec/ing36ar5r59

[60] MAE, *Estrategia Nacional de Cambio Climático del Ecuador: ENCC 2012–2025.* Quito, Ecuador: Ministerio del Ambiente del Ecuador, 2012, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r60

[61] R. Gomelsky, "Sustainable energy for all: Rapid assessment Gap analysis Ecuador," Ministry of Electricity and Renewable Energy (MEER), Quito, Ecuador, Tech. Rep., 2013, prepared within the Sustainable Energy for All (SE4ALL) initiative. Accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r61

[62] OER-LAC, "Renewable energy case of Ecuador," Organización Latinoamericana de Energía (OLADE), Brasilia, Brazil, Tech. Rep., Aug. 2011, final Report, Accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r62

[63] IPCC, *Global Warming of 1.5°C.* Geneva, Switzerland: World Meteorological Organization, Intergovernmental Panel on Climate Change, 2018, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r63

[64] C. B. Field, V. Barros, T. F. Stocker, Q. Dahe, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, and P. M. Midgley, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2012, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r65

[65] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J. C. Minx, *Climate Change 2014: Mitigation of Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014. [Online]. Available: https://upsalesiana.ec/ing36ar5r66

[66] IRENA, "Renewable energy benefits: Measuring the economics," International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, Tech. Rep., Jan. 2016, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r67

[67] IEA, *Energy Efficiency.* OECD, Oct. 2017. [Online]. Available: https://doi.org/10.1787/9789264284234-en

[68] ——, *World Energy Outlook.* Organisation for Economic Co-operation and Development, Nov. 2018. [Online]. Available: https://doi.org/10.1787/weo-2018-en

[69] ——, *Key World Energy Statistics.* Organisation for Economic Co-operation and Development, Oct. 2019. [Online]. Available: https://doi.org/10.1787/71b3ce84-en

[70] ——, *World Energy Balances.* Organisation for Economic Co-operation and Development, 2019. [Online]. Available: https://doi.org/10.1787/3a876031-en

[71] ——, *World Energy Statistics.* Organisation for Economic Co-operation and Development (OECD), 2019. [Online]. Available: https://doi.org/10.1787/2e828dea-en

[72] A. Azhaginiyal and G. Umadevi, "System dynamics simulation modeling of transport, energy and emissions interactions," *Civil Engineering and Architecture*, vol. 2, no. 4, pp. 149–165, Apr. 2014. [Online]. Available: http://doi.org/10.13189/cea.2014.020401

[73] A. Barisa and M. Rosa, "A system dynamics model for CO_2 emission mitigation policy design in road transport sector," *Energy Procedia*, vol. 147, pp. 419–427, Aug. 2018. [Online]. Available: http://doi.org/10.1016/j.egypro.2018.07.112

[74] J. Lemke and M. Małgorzata, "Validation of system dynamics models – a case study," *Journal of Entrepreneurship, Management and Innovation*, vol. 9, no. 2, pp. 45–59, 2013. [Online]. Available: http://doi.org/10.7341/2013923

[75] A. Maciąg, R. Pietroń, and S. Kukla, *Prognozowanie i symulacja w przedsiębiorstwie*, 1st ed. Warszawa: Polskie Wydawnictwo Ekonomiczne (PWE), 2013, accessed: 2026-05-19. [Online]. Available: https://upsalesiana.ec/ing36ar5r77

[76] M. Martis, "Validation of simulation based models: A theoretical outlook," *Electronic Journal of Business Research Methods*, vol. 4, 11 2006. [Online]. Available: https://upsalesiana.ec/ing36ar6r78

[77] J. Sterman, *Business Dynamics, System Thinking and Modeling for a Complex World.* McGraw-Hill Higher Education, 01 2000, vol. 19. [Online]. Available: https://upsalesiana.ec/ing36ar6r79

[78] R. C. a. Shreckengost, "Dynamic simulation models: how valid are they?" *PsycEXTRA Dataset*, 1985. [Online]. Available: http://doi.org/10.1037/e496952006-007

[79] Y. Barlas and K. Kanar, "A dynamic pattern-oriented test for model validation," *Boğaziçi University Research*, 01 1999. [Online]. Available: https://upsalesiana.ec/ing36ar6r81

[80] J. D. Sterman, "All models are wrong: Reflections on becoming a systems scientist," *System Dynamics Review*, vol. 18, no. 4, pp. 501–531, Dec. 2002. [Online]. Available: http://doi.org/10.1002/sdr.261

[81] ——, *Feedback complexity in integrated climate-economy models.* Massachusetts Institute of Technology, 1997. [Online]. Available: https://upsalesiana.ec/ing36ar6r83

[82] L. Režný and V. Bureš, "Energy transition scenarios and their economic impacts in the extended neoclassical model of economic growth," *Sustainability*, vol. 11, no. 13, p. 3644, 2019. [Online]. Available: https://doi.org/10.3390/su11133644

[83] C. Zou, Q. Zhao, G. Zhang, and B. Xiong, "Energy revolution: From a fossil energy era to a new energy era," *Natural Gas Industry B*, vol. 3, no. 1, pp. 1–11, Jan. 2016. [Online]. Available: https://doi.org/10.1016/j.ngib.2016.02.001

[84] F. V. Bekun, M. P. Fumey, M. W. Staniewski, L. Sun, and P. O. Agboola, "Energy intensive growth and the transition pathways: Insights into the role of renewable energy and open market conditions in developing countries," *Energy*, vol. 322, p. 135192, May 2025. [Online]. Available: https://doi.org/10.1016/j.energy.2025.135192

[85] K. Abbass, N. Amin, F. Khan, H. Begum, and H. Song, "Driving sustainability: The nexus of financial development, economic globalization, and renewable energy in fostering a greener future," *Energy & Environment*, Jan. 2025. [Online]. Available: https://doi.org/10.1177/0958305X241305374

[86] W. Zhao, X. Wang, and Y. Yan, "The substitution of fossil fuels for renewables in the electricity mix of China: From the perspectives of generation, capacity, and demand," *Energy*, vol. 315, p. 134364, Jan. 2025. [Online]. Available: https://doi.org/10.1016/j.energy.2025.134364

[87] A. Barragán-Ocaña, E. Cecilio-Ayala, P. Silva-Borjas, J. A. Cortés-Ruiz, and E.-Y. Hernández-Cardona, "Policies and sustainable energy transition in the global environment: Challenges for Latin America," *Heliyon*, vol. 11, no. 6, p. e42295, Mar. 2025. [Online]. Available: https://doi.org/10.1016/j.heliyon.2025.e42295

[88] A. J. Calderón Márquez, B. Smyth, A. F. Simões, and M. P. da Cunha, "Designing inclusive energy transitions: Insights from latin america's electricity sector," *Societal Impacts*, vol. 6, p. 100153, Dec. 2025. [Online]. Available: https://doi.org/10.1016/j.socimp.2025.100153

[89] P. Chavda and D. Mehta, "Assessing the impact of fossil fuel subsidies and environmental tax on renewable energy consumption of OECD countries: A panel quantile approach," *Next Energy*, vol. 8, p. 100313, 2025. [Online]. Available: https://doi.org/10.1016/j.nxener.2025.100313

[90] K. Bayramoğlu, M. Bayraktar, A. Seyhan, and O. Yuksel, "Evaluation of techniques to reduce carbon emissions from ships within the scope of revised greenhouse gas emission targets for 2030, 2040, and 2050," *Ocean Engineering*, vol. 334, p. 121605, Aug. 2025. [Online]. Available: https://doi.org/10.1016/j.oceaneng.2025.121605